MAKING CRATER CHAINS ON THE EARTH AND MOON WITH PLANETARY TIDAL FORCES. W. F. Bottke, Jr., *Caltech 170-25, Pasadena CA 91125, USA, bottke@kepler.gps.caltech.edu*, D. C. Richardson, *Box 351580, University of Washington, Seattle WA 98185, USA*, S. G. Love, *Caltech 252-21, Pasadena CA 91125, USA.*

Abstract

Crater chains, thought to form when "rubble-pile" asteroids or comets are pulled apart by planetary tides, may have been identified on both the Earth and Moon. By modeling the tidal disruption by the Earth and Moon of such objects, we find that enough bodies have been disrupted by the Earth over the last 3.8 billion years to account for one or two lunar crater chains. The disruption rate of bodies near the Moon, however, is too low to explain any terrestrial crater chains.

Definition of a Crater Chain

A crater chain is defined as a regularly spaced row of three or more impact craters with similar sizes and apparently identical ages. They are formed when a weak asteroid or comet is disrupted by tidal forces during a close approach to a planet. As the fragments recede from the planet, they reaccrete into many similarly-sized bodies which lie along a line (i.e. a "string of pearls" similar to that of Comet D/Shoemaker-Levy-9, or "SL9"). The fragment train then impacts a moon of the planet rather than escaping to interplanetary space.

Crater Chain Observations

Nearly twenty crater chains have been found on Ganymede and Callisto [1] They tend to be linear, ranging between 60–626 km in length. Each chain has between 6–25 closely spaced, similarly sized craters. It is now thought that one or two analogous crater chains exist on the Moon. They include the Davy chain, which is 47 km long and contains 23 craters, each 1–3 km in diameter, and the Abulfeda chain, which is ≥ 3.8 Gyr old, 200–260 km long and has 24 craters, each 5–13 km in diameter [2]. More recently, it has been speculated that one or two chains might even exist on the Earth. One potential chain is a 700 km line of eight circular depressions crossing Kansas, Missouri, and Illinois [3]. Each depression is 3–17 km wide. A second potential chain is located in Chad, where two possible impact features discovered by radar lie near the 17 km diameter, 360 Myr old Aorounga impact structure [4]. Both of these claims are controversial and need to verified by field work.

The Model

The same tidal break-up mechanism that makes crater chains on the Galilean satellites may also make them on the Earth and Moon. To investigate this idea, we simulate the tidal disruption of km-sized bodies by the Earth and Moon to measure the rate at which each causes crater chains on the other. We then compare our results to the observations described above. (*Alternative formation mechanisms are discussed in an accompanying LPSC abstract by Love, Bottke, and Richardson.*)

We model the progenitor as a "rubble-pile", a collection of 247 identical spherical particles held together by self-gravity. The progenitor's bulk density is 2 g cm^{-3}, similar to porous stone and consistent with the densities of Phobos and Deimos [5]. Individual particles have a density of 3.6 g cm^{-3}, similar to chondritic meteorites. The tidal disruption code itself is similar to codes used in the past by other groups [6, 7, 8]. We introduce, however, several modifications which allow us to more realistically treat close encounters between planets and rubble-pile progenitors: (a) We include friction between the particles, (b) We use non-spherical progenitors with dimensions of $2.8 \times 1.7 \times 1.5$ km ($1.8 \times 1.1 \times 1.0$ normalized), similar to the elongated shape of many near-Earth objects [9, 10], (c) We allow our progenitors to rotate with spin periods $P = 4, 6, 8, 10$, and 12 hours, similar to those of most Earth-crossing asteroids (ECAs) [11], (d) We test progenitors on hyperbolic encounters with the Earth and Moon, defined using the periapse distance q and pre-encounter velocity "at infinity" v_∞.

Results

Fig. 1 shows the results for progenitors with $P = 6$ h (prograde) encountering the Earth and Moon over various values of q and v_∞. The outcome classes are defined in the figure caption. We find that "S" class disruptions form lines of clumps of roughly equal size, analogous to the fragments seen in SL9. In all cases tested, only "S" class events produced fragment trains with orientations, sizes, and spacings consistent with the Moon's observed crater chains.

For the Moon, we find that "S" class events occur when $q \leq 1.2 R_{\text{Moon}}$ and $v_\infty \leq 2$ km s^{-1}. Other types of tidal disruption ("B", "M" class events, see Fig. 1) occur over a larger range of q and v_∞, but they cannot produce crater chains on Earth.

For the Earth, the regime of "S" class outcomes is much larger, ranging from $q \sim 2R_\oplus$ at 3 km s^{-1} to $q \sim 1.2R_\oplus$ for 12 km s^{-1}. We also find that bodies approaching within $q = 1.01 R_\oplus$ suffer "S" class disruptions even if their encounter velocities are as high as 21 km s^{-1}. The Earth's greater effectiveness at producing tidal disruptions can be explained by its higher density and larger size [6].

Results for the other spin periods, although not shown here, were similar in character to those at $P = 6$ hours. We note, however, that break-up is enhanced for faster rotators and inhibited for slower rotators.

The role of the progenitor's rotation pole orientation and phase angle were also examined. We found that objects with retrograde rotations typically suffer little mass loss (i.e. 50% of all progenitors). In addition, we found little mass was lost if the

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long axis of the progenitor was rotating away from the planet at periapse (50% of all progenitors). Assuming that ECAs have random pole orientations and phase orientations, we estimate that a given object has only a 25% chance of undergoing tidal disruption each time one encounters the Earth or Moon.

We use the results shown in Fig. 1 along with the geometrical considerations discussed above to calculate the mutual crater chain production rate on the Earth and Moon. Such an estimate, however, requires we know the impact cross-sections of the Earth and Moon as well as the flux, velocities, and spin rates of km-sized Earth-crossing asteroids. The probability of a body tidally disrupted by the Earth striking the Moon, or vice versa, is found by comparing the gravitational cross-section of the target body with the surface area of a sphere of radius D, where D is the Earth-Moon distance.

We estimate the ECA flux over time using estimates from [12] and [13]; we assume this flux has been constant for the last 3.0 Gyr [14]. The velocity distribution for ECAs with the Earth (or Moon) is given in [13]. The ECA rotation rate distribution is derived from [11].

We also account for higher crater chain formation rates in the past, due to an increased ECA flux (e.g. Late Heavy Bombardment [14]) and a smaller Earth-Moon separation distance [15].

Including all these effects over the 3.8 Gyr since the Late Heavy Bombardment, we find that there should be ~ 1 crater chain on the Moon, matching observations. The number expected on the Earth over the same time, however, is less than 0.1. In addition, the number expected on Earth over the last 360 Myr is only 0.001, inconsistent with either of the speculated terrestrial crater chains.

Conclusions

Because we expect the same population of bodies to encounter both the Earth and Moon, many of the uncertainties in this calculation are eliminated if we evaluate the ratio (rather than absolute numbers) of crater chains on the Earth and Moon. Our results show that the production rate of crater chains on the Moon is ~ 10 times the terrestrial rate. Thus, if there are two crater chains on the Earth less than 360 Myr old, we would expect about 20 young, fresh crater chains to be found on the Moon's near side. None are seen. We, therefore, believe that the reported terrestrial crater chains, if real, were not produced by asteroids or comets disrupted by lunar tides.

If later field work does indeed verify that the terrestrial crater chains are real, then our results suggest they are probably secondaries from an unseen (i.e. subducted or eroded away) or unrecognized large terrestrial crater. Lunar crater chains, however, can be explained by our model, suggesting that the tidal disruption of asteroids near Earth is more common than previously thought.

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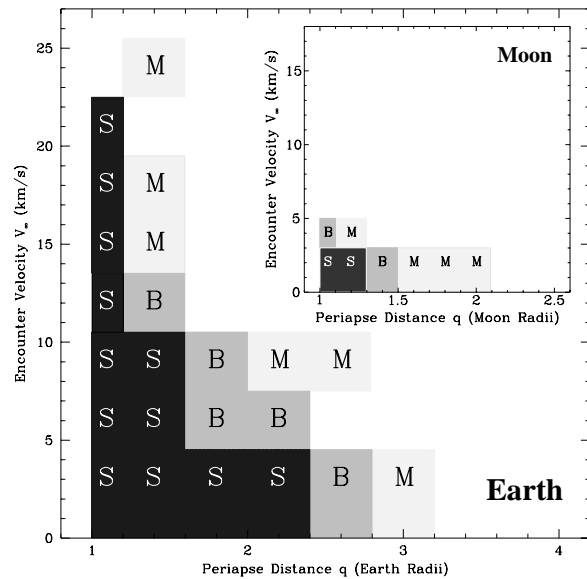

Figure 1: Tidal disruption outcomes for rubble-pile progenitors with rotation periods of $P = 6$ hours encountering both the Moon and the Earth. The outcomes, in decreasing order of severity are: (S) "Shoemaker-Levy-9-type" catastrophic disruption where the progenitor forms into a line of $\sim$ equal size clumps (i.e. a "string of pearls") and leaves less than 50% of its mass in the largest fragment; (B) Break-up with mass shedding of clumps and single particles, leaving the progenitor with 50%–90% of its original mass; and (M) Mild mass shedding of clumps or particles, leaving the progenitor with over 90% of its original mass. A fourth class, (N), corresponding to possible changes in the progenitor's shape or spin with no mass loss, fills the blank spaces on each plot. The jitter seen in the outcomes is caused by noise. The paucity of S-class events seen near the Moon is partially caused by the gravitational acceleration of the Earth, which substantially increases the periapse velocities of low v_∞ bodies.